A PHENOMENOLOGICAL OUTLOOK ON THREE-FLAVOR ATMOSPHERIC NEUTRINO OSCILLATIONS

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The recent observations of atmospheric ν events from the Super-Kamiokande experiment are compatible with three-flavor neutrino oscillations, occurring dominantly in the $\nu_\mu \leftrightarrow \nu_\tau$ channel and subdominantly in the $\nu_\mu \leftrightarrow \nu_e$ channel. We present an updated analysis of the three-flavor mass-mixing parameters consistent with the present phenomenology, including the latest 45 kTy data sample from Super-Kamiokande. A comparison with our previous results, based on 33 kTy data, shows that the oscillation evidence is strengthened, and that the neutrino mass-mixing parameters are constrained in smaller ranges.

1 Introduction

The recent atmospheric neutrino data from the Super-Kamiokande (SK) experiment [1] are in excellent agreement with the hypothesis of flavor oscillations generated by nonzero neutrino mass and mixing [2] in the $\nu_\mu \leftrightarrow \nu_\tau$ channel [3]. Such hypothesis is consistent with all the SK data, including sub-GeV e-like and μ-like events (SG$e,\mu$) [4], multi-GeV e-like and μ-like events (MG$e,\mu$) [5], and upward-going muon events (UPμ) [6], and is also corroborated by independent atmospheric neutrino results from the MACRO [7] and Soudan-2 [8] experiments, as well as by the finalized upward-going muon data sample from the pioneering Kamiokande experiment [9]. Oscillations in the $\nu_\mu \leftrightarrow \nu_\tau$ channel are also compatible with the negative results of the reactor experiment CHOOZ in the $\nu_\mu \leftrightarrow \nu_e$ channel [10].

However, it has been realized that *dominant* $\nu_\mu \leftrightarrow \nu_\tau$ oscillations plus *subdominant* $\nu_\mu \leftrightarrow \nu_e$ oscillations are also consistent with SK+CHOOZ data, and lead to a much richer three-flavor oscillation phenomenology [11]. A detailed 3ν analysis of the SK observations, including the full 33 kTy data sample, can be found in Ref. [11]. Here we report and comment briefly the results of our updated analysis, based on the recent 45 kTy SK data [12,13]. The theoretical framework is based on the so-called one mass scale dominance [14], which has been used also for three-flavor oscillation studies of pre-SK atmospheric and reactor neutrino data in Refs. [14,15,16].

2 3ν analysis of SK phenomenology (45 kTy)

In the hypothesis that the two lightest neutrinos (ν_1, ν_2) are effectively degenerate $(m_1^2 \simeq m_2^2)$ (one mass scale dominance), it can be shown [14,11] that atmospheric neutrinos probe only $m^2 \equiv m_3^2 - m_{1,2}^2$, together with mixing matrix elements $U_{\alpha i}$ related to ν_3, namely:

$$\text{Parameter space} \equiv (m^2, U_{e1}^2, U_{e2}^2, U_{e3}^2) , \tag{1}$$

where $U_{e1}^2 + U_{e2}^2 + U_{e3}^2 = 1$ for unitarity. The unitarity constraint can be conveniently embedded in a triangle plot [14,15,11], whose corners represent the flavor eigenstates, while the heights projected from any inner point represent the $U_{\alpha 3}^2$'s.

Within this framework, we analyze 30 data points, related to the zenith distributions of sub-GeV events (SG e-like and μ-like, 5+5 bins), multi-GeV events (MGe,μ 5+5 bins) and upward-going muons (UPμ, 10 bins), using the latest 45 kTy SK sample [12,13]. We also consider the rate of events in the CHOOZ reactor experiment [10] (one bin), which constrains the ν_e disappearance channel. Constraints are obtained through a χ^2 statistic, as described in Ref. [11].

Figure 1 shows the regions favored at 90% and 99% C.L. in the triangle plot, for representative values of m^2. The CHOOZ data, which exclude a large horizontal strip in the triangle, appear to be crucial in constraining three-flavor mixing. Pure $\nu_\mu \leftrightarrow \nu_e$ oscillations (right side of the triangles) are excluded by SK and CHOOZ independently. The center of the lower side, corresponding to pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with maximal mixing, is allowed in each triangle both by SK and SK+CHOOZ data. However, deviations from maximal $(\nu_\mu \leftrightarrow \nu_\tau)$ mixing, as well as subdominant mixing with ν_e, are also allowed to some extent. Such deviations from maximal 2ν mixing are slightly more constrained than in the previous analysis of the 33 kTy SK data [11].

Figure 2 shows the constraints on the mass parameter m^2 for unconstrained three-flavor mixing. The best fit value is reached at $m^2 \sim 3 \times 10^{-3}$ eV^2, and is only slightly influenced by the inclusion of CHOOZ data. However, the upper bound on m^2 is significantly improved by including CHOOZ. As compared with the corresponding plot in Ref. [11] (33 kTy), this figure shows that the 45 kTy data are in better agreement with the oscillation hypothesis (lower χ^2). Moreover, the favored range of m^2 is restricted by $\sim$ 10% with respect to Ref. [11].

Figures 1 and 2 clearly show the tremendous impact of the SK experiment in constraining the neutrino oscillation parameter space. Prior to SK, the data could not significantly favor $\nu_\mu \leftrightarrow \nu_\tau$ over $\nu_\mu \leftrightarrow \nu_e$ oscillations, and could only put weak bounds on m^2 (see Refs. [15,16]).

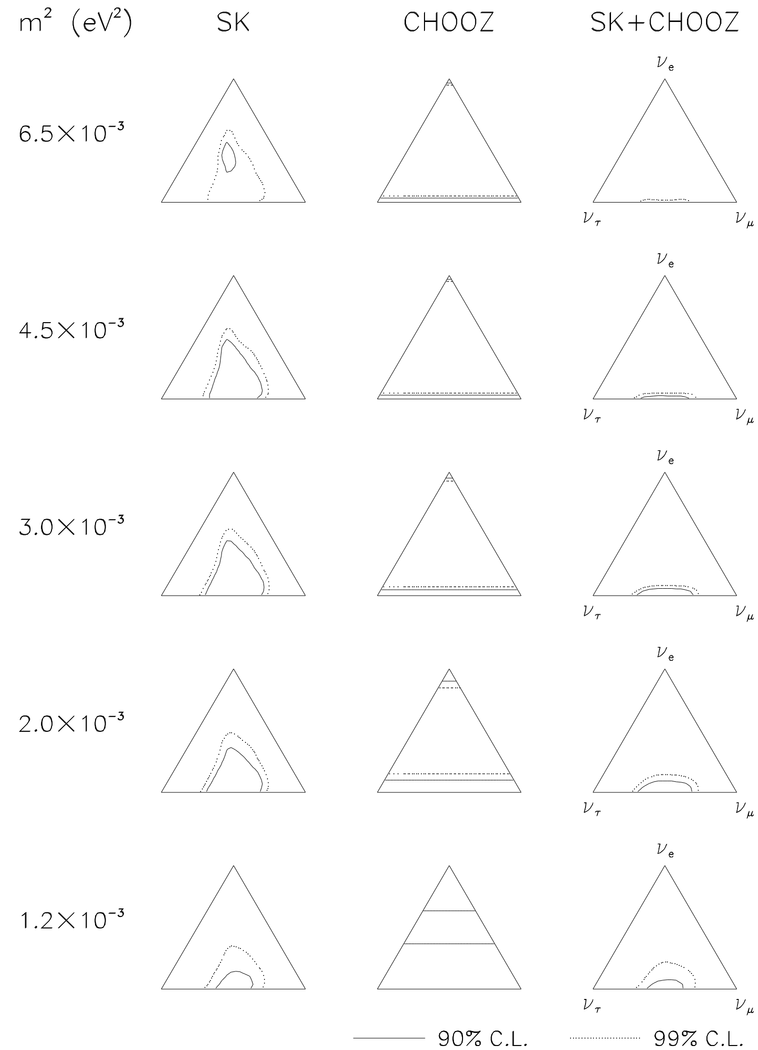

Figure 1: Three-flavor analysis in the triangle plot, for five representative values of m^2. Left and middle column: separate analyses of Super-Kamiokande (45 kTy) and CHOOZ data, respectively. Right column: combined SK+CHOOZ allowed regions. Although the SK+CHOOZ solutions are close to pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, the allowed values of U^2_{e3} are never negligible, especially in the lower range of m^2.

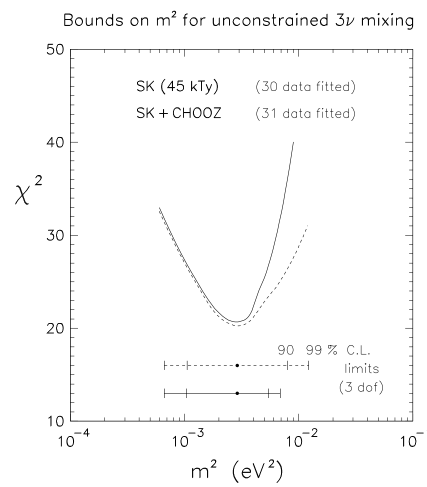

Figure 2: Values of χ^2 as a function of m^2, for unconstrained three-flavor mixing. Dashed curve: fit to SK data only (45 kTy). Solid curve: fit to SK+CHOOZ. The minimum of χ^2 is reached for $m^2 \simeq 2.8 \times 10^{-3}$ eV^2.

Finally, Fig. 3 shows the best-fit zenith distributions of SG$e, \mu$, MG$e, \mu$, and UPμ events, normalized to the no-oscillation rates in each bin. There is excellent agreement between data and theory, especially for the μ distributions. The nonzero value of U^2_{e3} at best fit leads to a slight expected electron excess in the MGe sample for $\cos\theta \to -1$. The observed electron excess is, however, somewhat larger than expected, both for SGe's and for MGe's. A significant reduction of the statistical error is needed to probe possible MGe distortions, which would be unmistakable signals of subdominant $\nu_\mu \to \nu_e$ oscillations.

3 Outlook

The Super-Kamiokande data are compatible with three-flavor oscillations dominated by $\nu_\mu \leftrightarrow \nu_\tau$ transitions. The amplitude of the $\nu_\mu \leftrightarrow \nu_e$ channel is not necessarily zero, although being strongly constrained by both SK and CHOOZ. A contribution from the $\nu_\mu \leftrightarrow \nu_e$ channel might explain part of the electron excess observed in SK, especially for multi-GeV e-like events. Higher statistics is needed to test such interpretation. A definite progress in confirming the oscillation hypothesis, and in constraining the mass-mixing parameters, emerges from a comparison of the 33 kTy and 45 kTy SK data analyses.

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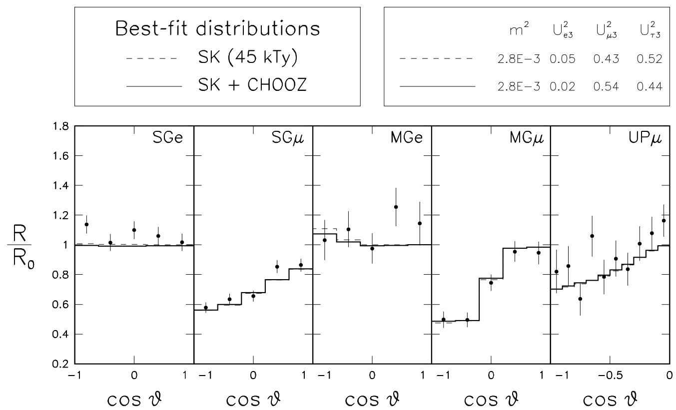

Figure 3: SK zenith distributions of leptons at best fit (dashed lines), also including CHOOZ (solid lines), as compared with the 45 kTy experimental data (dots with error bars). The 3ν mass-mixing values at best fit are indicated in the upper right corner.

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